Quiet Honeycomb Panels

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Sandwich honeycomb composite panels are lightweight and strong, and, therefore, provide a reasonable alternative to the aluminum ring frame/stringer architecture currently used for most aircraft airframes. The drawback to honeycomb panels is that they radiate noise into the aircraft cabin very efficiently provoking the need for additional sound treatment which adds weight and reduces the material's cost advantage. A series of honeycomb panels was made which incorporated different design strategies aimed at reducing the honeycomb panels' radiation efficiency while at the same time maintaining their strength. The majority of the designs were centered around the concept of creating areas of reduced stiffness in the panel by adding voids and recesses to the core. The effort culminated with a reinforced/recessed panel which had 6 dB higher transmission loss than the baseline solid core panel while maintaining comparable strength.

1. INTRODUCTION

The application of composite materials to aircraft structures will decrease aircraft mass and change how aircraft are designed and constructed. The expectation is that the new materials will reduce the life cycle cost of the aircraft through lower manufacturing and operational costs. A representative model of current aircraft sidewall construction is shown in Fig. 1(a). The sidewall is composed of 3 major components, the aircraft skin, longitudinal stringers and circumferential ring frames. All the components are aluminum and are riveted together. The mass per unit area of the stiffened aluminum panel is 1.2 lb/ft² (5.9 kg/m²).

Contrast the aluminum sidewall to the honeycomb sandwich composite panel also shown in Fig. 1. Visually the differences are striking. The interior is smooth and the panel is much thinner than its aluminum counterpart, <1" (2.54cm) for the composite panel vs. >2.5" (6.35cm) for aluminum panel. This gives the designers the freedom to set a smaller diameter fuselage for a comparable interior space, saving even more weight beyond the 35% reduction the materials already provide, (the mass per unit area of the honeycomb panel is 0.79 lb/ft² (3.9 kg/m²)).

However, this weight savings comes at a cost in increased levels of interior noise. This trend is observed in transmission loss measurements where the acoustic power incident on the 'source' side of a panel is compared to the power on the 'receiving' side. A high transmission loss implies reduced interior

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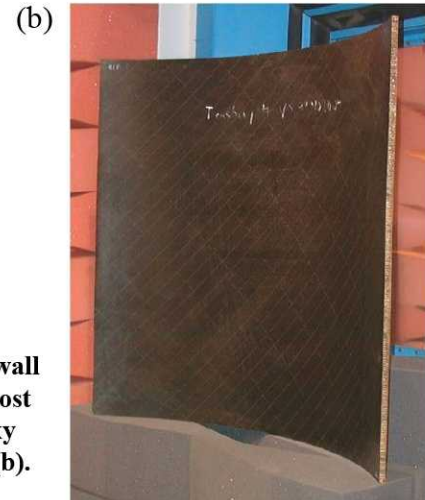
Fig. 1 Stiffened aluminum sidewall construction (a) is typical of most aircraft today. Graphite epoxy honeycomb panel is shown in (b).

noise. Fig. 2(a) shows the transmission loss of the stiffened aluminum panel compared to a flat honeycomb composite panel of construction similar to the curved panel. As can be seen, the honeycomb panel loses as much as 10 dB in transmission loss compared to the aluminum panel. This deficiency will have to be compensated by added acoustic treatment, reducing the weight benefit the manufacturer and it's customers expected to achieve. For these reasons, it is important to understand why the honeycomb panel has such poor noise performance and to investigate ways in which the noise penalty can be reduced while maintaining the weight advantage these new materials bring to aerospace vehicle design. The following section will discuss some of the theory behind the honeycomb composite panel's behavior. Subsequent sections will present the results of testing various instances of honeycomb panels that were built to understand how the goal of increased transmission loss without appreciable weight gain might be achieved.
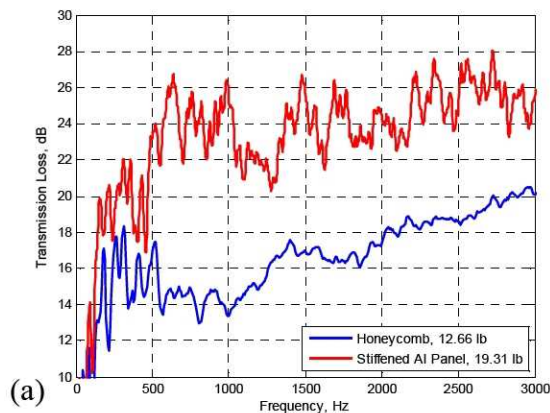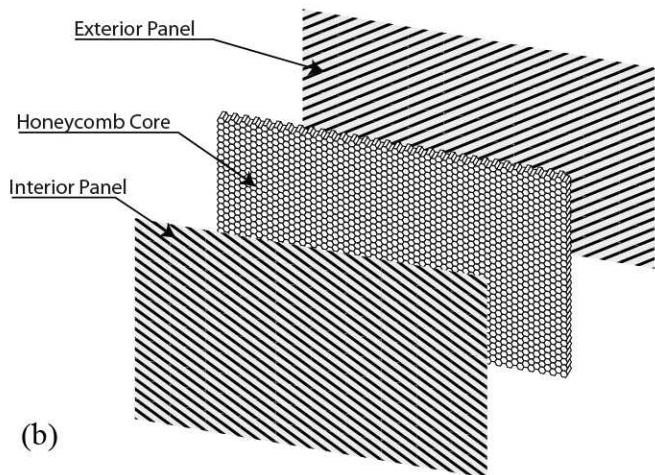
Fig. 2 Transmission loss of stiffened aluminum panel and solid core honeycomb panel (a), band average difference in TL (b), and components of honeycomb sandwich panel (c).

Average Difference in TL Over Frequency Band

100-500	500-1000	1000-2000	2000-5000
4.2	9.7	7.2	5.5

1.1 Structural Acoustics Background

A sandwich core composite panel is composed of three components, the core and the inner and outer face sheets, Fig. 2(b). The components can be made of many different kinds of materials depending on the application. For example, the core is often foam in lightweight partitions, but is stiffer honeycomb in load bearing panels. Likewise, the face sheets can be sheet metal, fiberglass or carbon fiber. The benefit

of the sandwich core design is that a lightweight and semi-rigid core material acts to increase the stiffness of the face sheets by virtue of their constrained displacement away from the composite panel's neutral axis. In this way the strength of the composite panel is greater than the sum of its parts.

The effect of the decreased mass and increased stiffness of the honeycomb panel can be seen in the respective panels' wavenumber spectra, Fig. 3. In the wavenumber spectrum plots displayed here and elsewhere, the total power in the panels is calculated as the sum of the squared velocity over the surface of the panel. The velocity was normalized by the input force. The color axis is in dB taking the total power in the solid core honeycomb panel as reference. The majority of the vibration energy in the stiffened aluminum panel is well above the sonic wavenumber (the black line), characteristic of a subsonic panel. The energy is also scattered due to the discrete nature of the panel's construction. In contrast, the power in the honeycomb panel, though much less than the aluminum panel, is concentrated around the sonic wavenumber, indicating its lighter weight, increased stiffness and more uniform construction. The panel is seen to be substantially supersonic by 400 Hz.
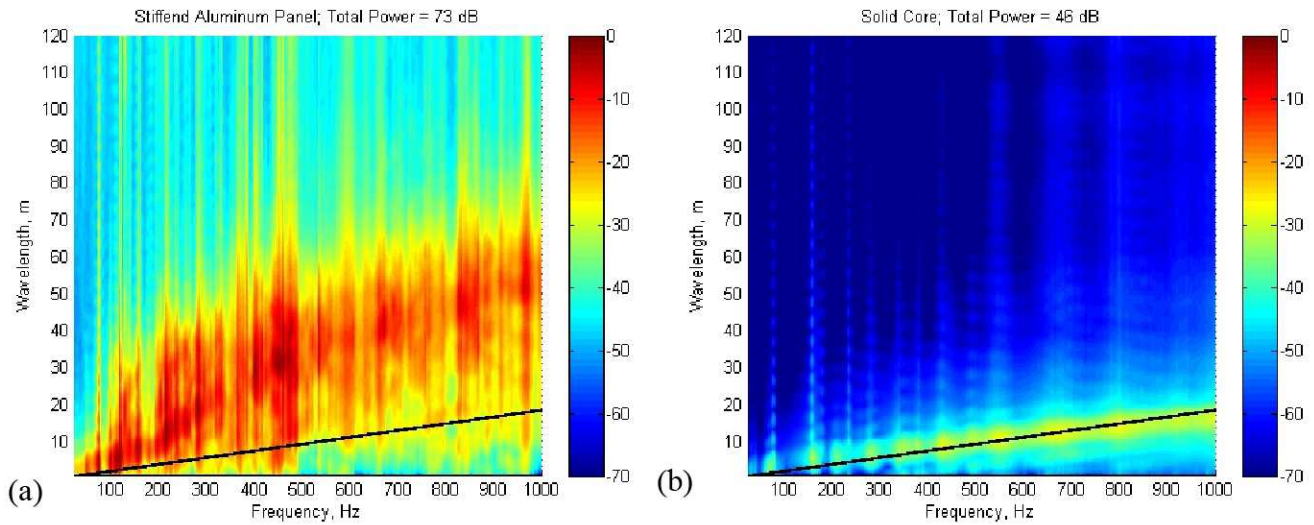

Fig. 3 Wavenumber spectra of stiffened aluminum panel (a) and solid core panel (b) compared to sonic wavenumber, black line.

The uniform construction of the honeycomb panel enables the excitation of almost ideal modes. The velocity response and related wavenumber spectrum for the honeycomb panel at 340 Hz is shown In Fig. 4(a). Note the very well defined 2,2 mode. The wavenumber spectrum of this response, Fig. 4(b), shows the energy is concentrated around the sonic circle. This curve illustrates why a panel's radiation is not always reduced by increasing panel stiffness. For a given excitation, a panel's velocity response will be inversely proportional to its stiffness. Intuitively, one might expect the sound radiation to decrease as panel stiffness increases. However, as stiffness increases, the panel's energy, as represented by the modal nodes in Fig. 4(b), moves towards the sonic circle, increasing the proportion of the total panel energy that is radiating efficiently. This increase in radiation efficiency overwhelms the decrease in vibration up to the point where most of the energy is within the sonic circle. After that, an increase in stiffness will reduce noise radiation as expected.

1.2 Approach to the problem

The design challenge presented was how to reduce the panel's radiation without increasing its mass and without decreasing its load bearing capability. The approach taken was to reduce the surface area of the panel which supports supersonic waves. This was accomplished by milling the core in different
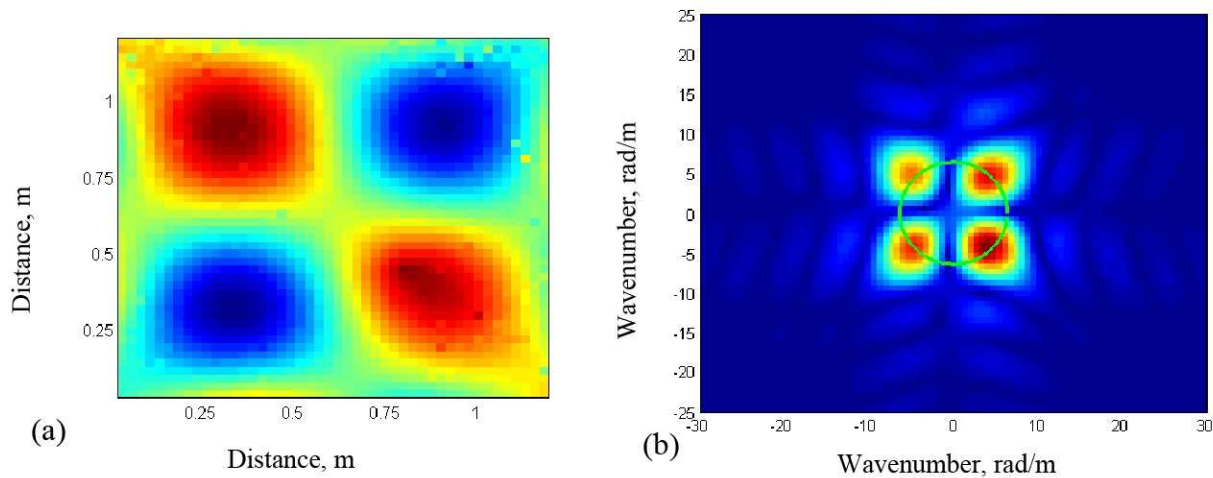
Fig. 4 Velocity response (a) and wavenumber spectrum (b) of solid core honeycomb panel at 340 Hz, 2,2 mode. Sonic circle shown as green line in (b).

locations so that one or both face sheets were not bonded to the core in these locations. The initial 2 designs which resulted from this approach were the voided and recessed core panels, Fig. 5 (a) and Fig. 9(a) respectively. The voided core had areas where the core was completely removed. This resulted in a core structure which resembled the aluminum panel's ring frame/stringer architecture. The voids also created areas of double wall features which would have a positive acoustic benefit.

To make the recessed core, core material was milled to a prescribed depth, from one side of the panel. This was done initially to accommodate automated lay-up tools which would need a continuous surface on at least one side of the panel to lay down the carbon fiber tape. As will be seen in later sections, the remaining core not only provided acoustic benefit by damping transverse modes in the cavity, but also served as a base for increasing the panel's stiffness through the addition of a third, internal face sheet.

Another consideration in taking this approach was that it would break up the baseline panel's uniform architecture and scatter the panel's vibration energy into many wavenumbers, thus reducing the energy concentrated around the sonic circle. While this effect was observed, its benefit was hard to quantify. Finally, it was expected that the voided and recessed panels would lose stiffness with respect to the baseline panel. To address this, finite element models of the panels were created and an optimal design was achieved which gave up some of the acoustic gains for additional stiffness[2,3].

It should be noted that all the panels were made using the same core material with the same core dimensions. The composite panel's stiffness could have been increased, for example, by increasing the core thickness. This dimension of the design space was not explored.

1.3 Panel specifications and test procedures

A flat model of a stiffened aluminum sidewall (pictured in Fig. 1(a)) was used as a basis for comparison to the honeycomb panel. As mentioned earlier, the panel is composed of 3 distinct components, the skin, ring frames and stringers. All the components are aluminum. The skin is 0.050" (1.27mm) thick. The ring frames (the vertical stiffeners in Fig. 1(a)) are also made from 0.050" (1.27mm) material. The stringers are made from 0.040" (1.02mm) material. The components are riveted together as is typical of aircraft construction. The complete panel is 4'x4' (1.22mx1.22m) with a 1" (2.54 cm) flange provided for clamping into the test window (the 'working' section of the panel is then 46" (1.17m)) square. The sub-panel dimensions are 17.25 in. (43.8 cm) x 5.5 in (14 cm) and the completed panel weighs 19.31 lbs (8.8 kg).

The honeycomb panel is also composed of 3 major pieces, the 2 face sheets and the core. In practice, the face sheets are carbon fiber lay-ups. For test purposes, the face sheets were made from 0.020" (0.51mm) aluminum. This gives the panel the same approximate stiffness as one with carbon face sheets, with little added mass. The core is 0.75" (1.91cm) thick Nomex with hexagonal cells. The density of the core was 3 lbs/ft.^{3} (38 kg/m^3. The core and one face sheet is 46" (1.17m) square. The second face sheet is 48" (1.22m) square providing a 1" (2.54cm) flange that can be clamped into the test window. The baseline honeycomb panel weighed 12.66 lb (5.7 kg).

The panels were tested for transmission loss and velocity response in NASA Langley's Structural Acoustic Loads and Transmission (SALT) facility. The SALT facility is composed of an anechoic chamber (receiving room) and a reverb chamber (source room) with a test window which is visible in Fig. 1(a) separating the two. Transmission loss is calculated as the ratio of acoustic power radiated by the receiving side of the panel to the acoustic power incident on the source side. The incident acoustic intensity on the source side was derived from the average power in the reverb chamber as estimated by an array of 12 randomly spaced microphones. The transmitted normal acoustic intensity was measured in the anechoic chamber using intensity probes on a 2 in. x 3 in. (5.08 cm x 7.62 cm) grid 5 in. (12.7 cm) from the panel's surface. A 12mm spacer was used with the intensity probe which resulted in a 15 dB pressure-residual intensity index over the analysis band. The measured pressure-intensity index was 5 dB.

The wavenumber spectra were calculated as the spatial Fourier transform of the velocity response over the panel. The panels were excited with pseudo-random noise having a bandwidth of 100 to 2000 Hz using a 10 N shaker through an impedance head located at a point on the panel over solid core. In most cases this was 8 in (20.3 cm) form one side and 16 in (40.6 cm) from the other. The normal velocity structural response was measured with a scanning laser vibrometer. Velocity measurements were taken on a 1 in. x 1 in. (2.54 cm x 2.54 cm) grid.

Several variants of voided and recessed core panels were built and tested. They differed by the arrangement and construction of the voided/recessed features. The panels included the following range of architectures: a 3x3 array of 10" (25.4 cm) features, a 3x3 array of 6" (15.24 cm) features and a 5x5 array of 6" (15.24 cm) features. The following sections detail the construction and performance of panels with 3x3 10" (25.4 cm) features and summarize the performance of all the panels.

2. VOIDED CORE PANELS

2.1 Voided Core, 3x3 10" (25.4cm) squares, 11.15 lbs (5.2 kg)

The honeycomb core with 10" (25.4cm) voids is shown in Fig. 5(a). The transmission loss (TL) of the assembled panel is compared to the solid core panel in Fig. 5(b). The acoustic behavior of the voided panel is complicated by the many resonances, both structural and acoustic, introduced by the design. The voids will exhibit a mass-air-mass resonance due to the double wall construction and undamped cavity. This resonance can be seen as a pronounce dip in the TL at 400 Hz, followed by a distinct increase in TL. The increased TL achieved by the action of the double-wall is reduced by a second dip in TL which is seen to occur at about 650 Hz. This resonance is due to transverse modes in the cavity. The voided panel achieves a 6.9 dB increase in TL between 1 kHz and 2 kHz. Above 2 kHz, the increase in TL drops to 4.6 dB. The increase in TL is achieved in spite of a 12% decrease in mass compared to the solid core panel.
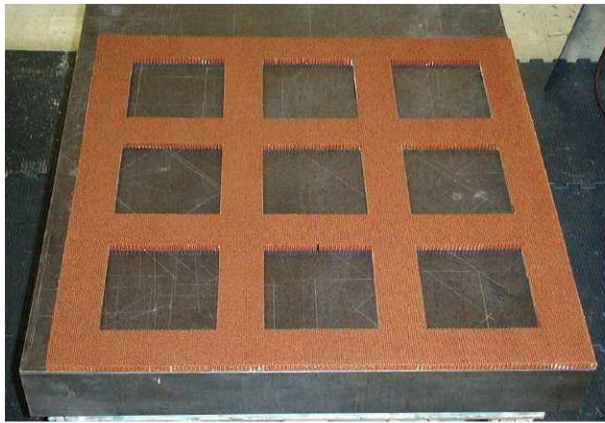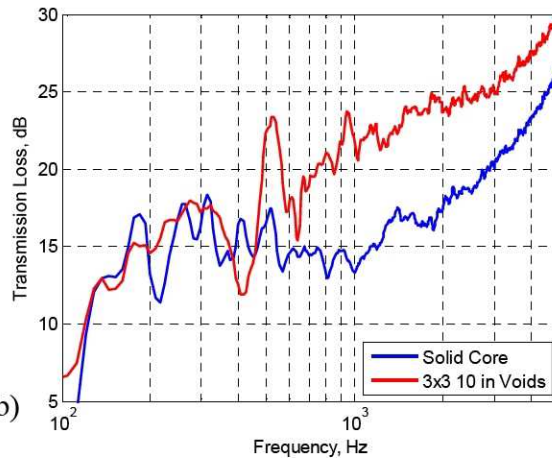
Fig. 5 Nomex core with 10" voids (a), transmission loss (b), and band average difference in TL, (c).

(a)

(b)

(c)

Average Difference in TL Over Frequency Band

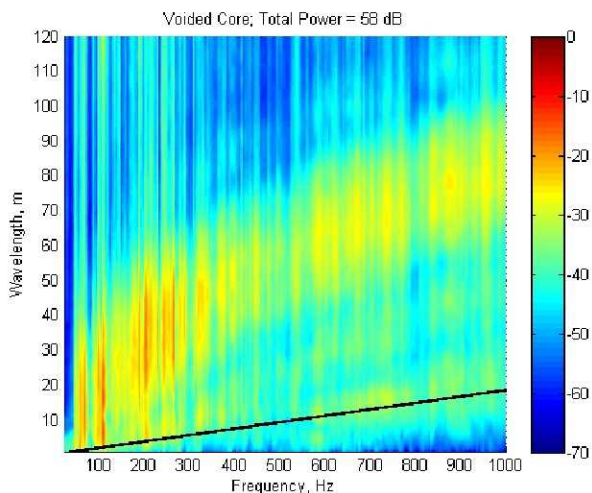| 100-500	500-1000	1000-2000	2000->5000
0.5	6.0	6.9	4.6

Fig. 6 Wavenumber

The wavenumber spectrum of the velocity response of the voided core panel in Fig. 6 has more in common with the aluminum panel, Fig. 3(a), than the solid core panel, Fig. 3(b). The total vibrational power is increased by 12 dB over the solid core panel. This is due to the unconstrained vibration of the panel over the voids. This part of the panel is substantially subsonic and produces most of the energy observed in Fig. 6 above the sonic line.

An open question at this point concerns the relative strength of the voided panel with respect to the aluminum and solid core panels. Assuming that the recessed core panel (described in "Recessed Core, 3x3 10" (25.4cm) squares, 12.15 lbs (5.5 kg)" on page 7) has a strength similar to the voided core, it can be inferred from deflection tests done on the recessed core panel that the voided core panel lacked substantial strength (see "Deflection tests" on page 11). Even if the core thickness is increased to recover stiffness, the panel sections over the voids would have to be reinforced to sustain pressurization loads. An optimum combination of thicker core and reinforced voids might result in a viable design.

2.2 Voided core, 3x3 10" (25.4cm) square, fiberglass filled, 11.37 lbs (5.2 kg)

Filling the voids with fiberglass removes the effects of acoustic resonances in the voids resulting in a 10 dB gain in TL above 500 Hz. A small dip in TL at the mass-air-mass resonance of 400 Hz is still visible. The combination of thicker core, thicker exterior face sheet and fiberglass filling may produce a strong yet substantially quieter panel.

**Fig. 7 Voided core with fiberglass fill (a), transmission loss (b), and band difference in TL, (c).**

(b)

(c)
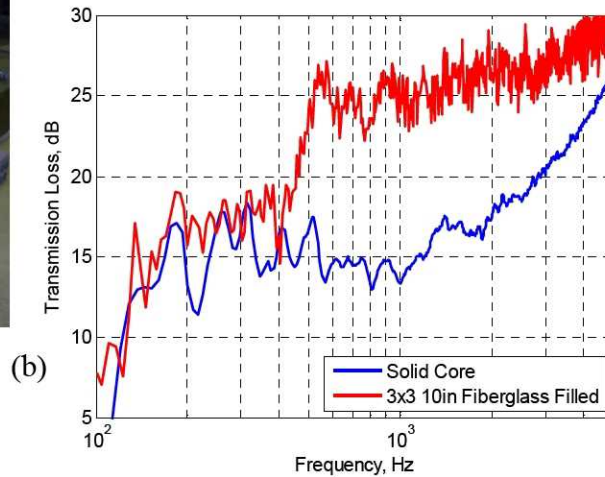
Average Difference in TL Over Frequency Band

100-500	500-1000	1000-2000	2000-5000
2.6	10.3	9.5	5.8

2.3 Comparison of voided core panels' performance

The difference in TL between the solid core, panel and the modified panels is plotted in Fig. 8. As noted earlier, this summary includes all the voided core panels built and tested. Below 500 Hz the panels' behaviors are similar. Above 500 Hz the fiberglass filled panel has the best performance with the 3x3 6" panel returning the poorest performance.
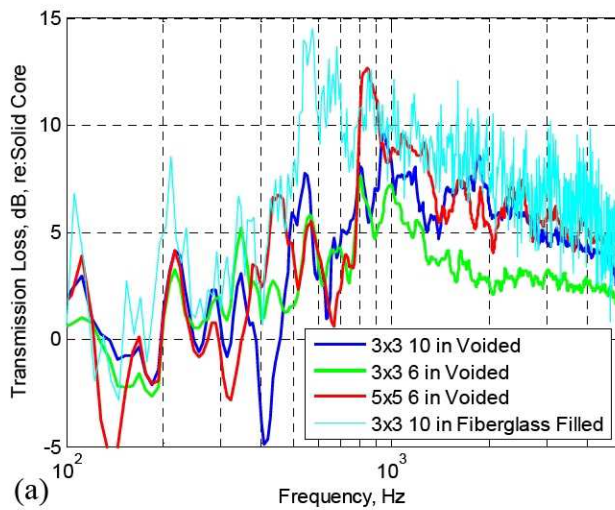
(a)

Average Difference in TL Over Frequency Band

Panel	100-500 Hz	500-1000 Hz	1000-2000 Hz	2000-5000 Hz
3x3, 10"	0.5	6.0	6.9	4.6
3x3, 6"	1.2	4.9	3.9	2.6
5x5, 6"	1.5	6.5	7.0	5.2
Fiber Filled	2.6	10.3	9.5	5.8

(b)

Fig. 8 Voided core panels' transmission loss with respect to baseline solid core panel (a) and band average differences in TL, (b).

3. RECESSED CORE PANELS

### 3.1 Recessed Core, 3x3 10" (25.4cm) squares, 12.15 lbs (5.5 kg)

The recessed core design was originally conceived to facilitate construction of assemblies using automated tape machines. In this process, the tape machine lays down the interior face sheet, the honeycomb is applied, then the tape machine lays down the exterior face sheet. This process would not work well with the voided core as the tape would sag over the voided areas. Using recessed core,

however, the honeycomb can be laid down with the recesses facing the interior. This would present a continuous surface on the exterior, so the tape machine would have no trouble applying the exterior layers of tape. The recesses in this panel are cut to a depth of 1/4" (0.64cm). During testing it was observed that the orientation of the recesses, i.e., whether they faced the source room or the receiving room, did not alter the transmission loss. Orientation would, of course, matter during vibration measurements which were done over the recessed side of the panel.

The recessed core had unanticipated acoustics benefits. The transmission loss, Fig. 9(b), is similar to the fiberglass filled panel, Fig. 7(b), with the exception of a dip in the TL around 600 Hz. This resonance is due to the same transverse modes that occur in the voided core panel that are now largely eliminated by the core except in the recess. The 'exterior' face sheet is bonded to the core so the effective mass and stiffness of the exterior face sheet increased, altering the mass-air-mass resonance and the effectiveness of the double wall.

(a)
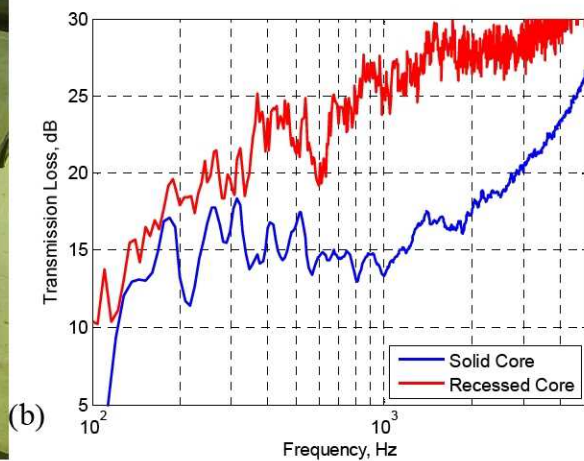
(b)

Fig. 9 Recessed core with 3x3 10" squares recesses, 0.25" deep (a), transmission loss (b) and band average difference in TL, (c). (c)

Average Difference in TL Over Frequency Band

100-500	500-1000	1000-2000	2000-5000
5.1	9.7	11.1	7.8

Compared to the voided core, the wavenumber spectrum of the recessed core, Fig. 10, has 6 dB less vibrational power overall and much less vibrational power around the sonic line throughout the frequency band, as would be expected given that the TL of the recessed core is 3-5 dB greater than the voided core.
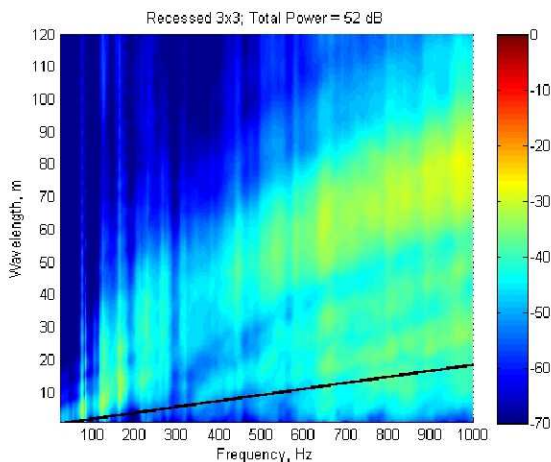

Fig. 10 Wavenumber spectrum of 3x3 10" recessed panel.

3.2 Reinforced core, 3x3 10" (25.4cm) squares, 14.1 lbs (6.4 kg)

Once it was determined that a good amount of TL headroom could be obtained using the recessed core design, the effort turned to restoring the lost stiffness. An optimization was performed using finite element analysis[2] which resulted in a panel with 5x5 0.5" (1.27 cm) recesses reinforced with 0.016" (0.4 mm) aluminum. To better understand the effect of adding the reinforcement, a 3x3 10" recessed panel was built with the reinforcing panels, Fig. 11(a). The TL of the reinforced panel, Fig. 11(b), is reduced 3-6 dB compared to the recessed panel, Fig. 9(b), despite

increasing mass 15%. The mass of the reinforced panel is about 10% greater than the solid core panel. The decrease in TL (and increase in mass) is due primarily to the introduction of the reinforcing interior panel. This TL penalty can largely be compensated by the inclusion of fiberglass in the recesses as was done in a subsequent panel, see the following section.
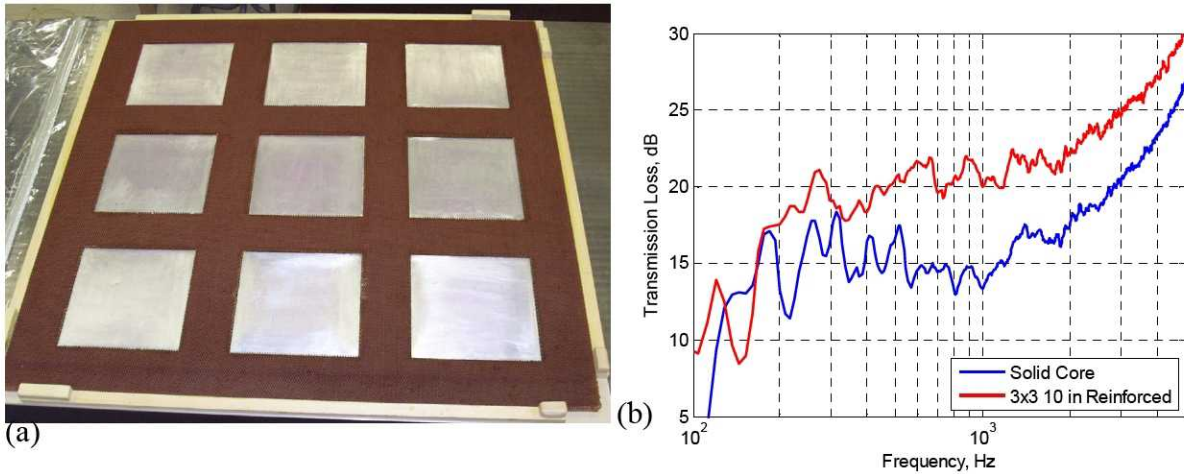

(a)

(b)

Fig. 11 Reinforced recessed core with 10" square recesses, 0.25" deep (a), transmission loss (b) and band averaged difference in TL, (c).

(c)

Average Difference in TL Over Frequency Band			
100-500	500-1000	1000-2000	2000-5000
3.0	6.4	5.1	4.2

The total vibrational power, Fig. 12(a) in the reinforced panel is just 1 dB greater than the recessed panel but more of that power is concentrated around the sonic line, increasing the radiated sound power. Some of the low frequency modes were moved closer to the sonic line and higher frequency modes (possibly coming from the interior panel) pop up around the sonic line. All these factors contribute to the observed decrease in TL.
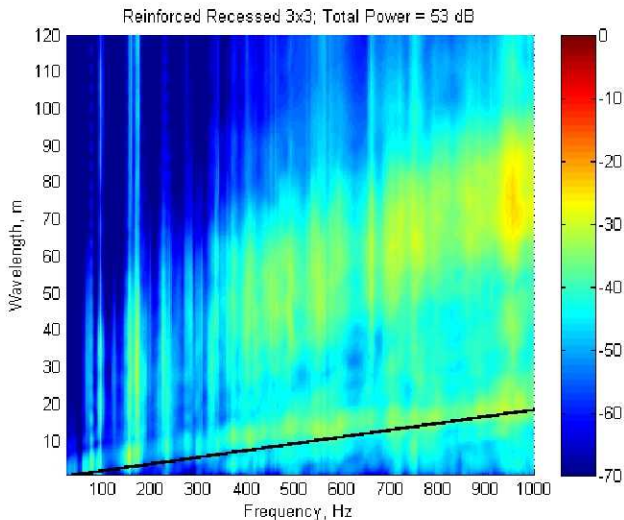

Fig. 12 Wavenumber spectrum of 3x3 10" reinforced panel.

3.3 Reinforced, fiberglass filled, 3x3 10" (25.4cm) squares, 13.8 lbs (6.3 kg)

As the benefit of filling panel voids with fiberglass had been demonstrated on a voided core panel, the last panel in this series was a reinforced core panel with the 1/4" recesses filled with fiberglass, Fig. 13(a). Unfortunately, at the time this panel was produced, the SALT was not configured for TL tests, and only vibration tests were conducted. The resulting wavenumber spectrum, Fig. 13(b), has 5 dB less total vibration power than the 3x3 reinforced panel, and much less power around the sonic line at the higher frequencies. The fiberglass does not affect the panel's global modes at the lower frequencies.

3.4 Comparison of recessed core panels' performance

As TL testing was not performed on the fiberglass treated reinforced panel, the comparisons must be done in 2 phases. The first compares the available TL data of the 3x3 and 5x5 recessed and reinforced
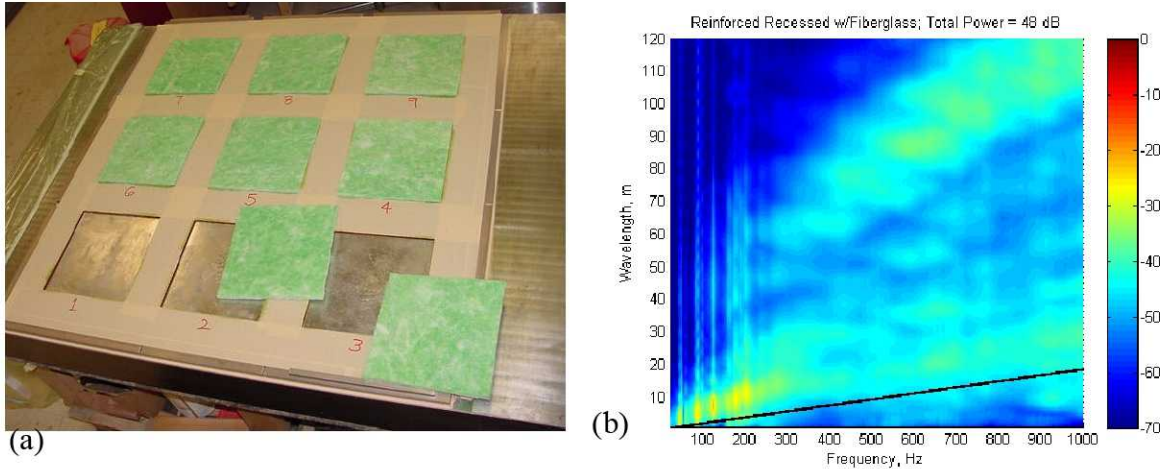
Fig. 13 Reinforced recessed core with 10 inch squares, fiberglass filled (a), wavenumber spectrum (b).

panels to the solid core panel, Fig. 14(a). As expected, the 3x3 recessed panel has the best performance. The optimized 5x5 panel achieves increases of TL of 3 dB over the 3x3 reinforced panel for 2 modes just below and above 400 Hz and 2 dB increase above 800 Hz. This increase in TL reduces as frequency increases. The improved performance of the 5x5 panel is due in part to a decrease in stiffness due to deeper, 0.5" (1.27 cm) recesses. The second phase compares the decrease in radiated sound power of the 3x3 panels with respect to the solid core panel, Fig. 14(b) (note that the ordinate axis is inverted). The fiberglass treated panel tracks the untreated panel up to 600 Hz where gains of 3 dB are achieved through damping of the cavity, Fig. 14(d).
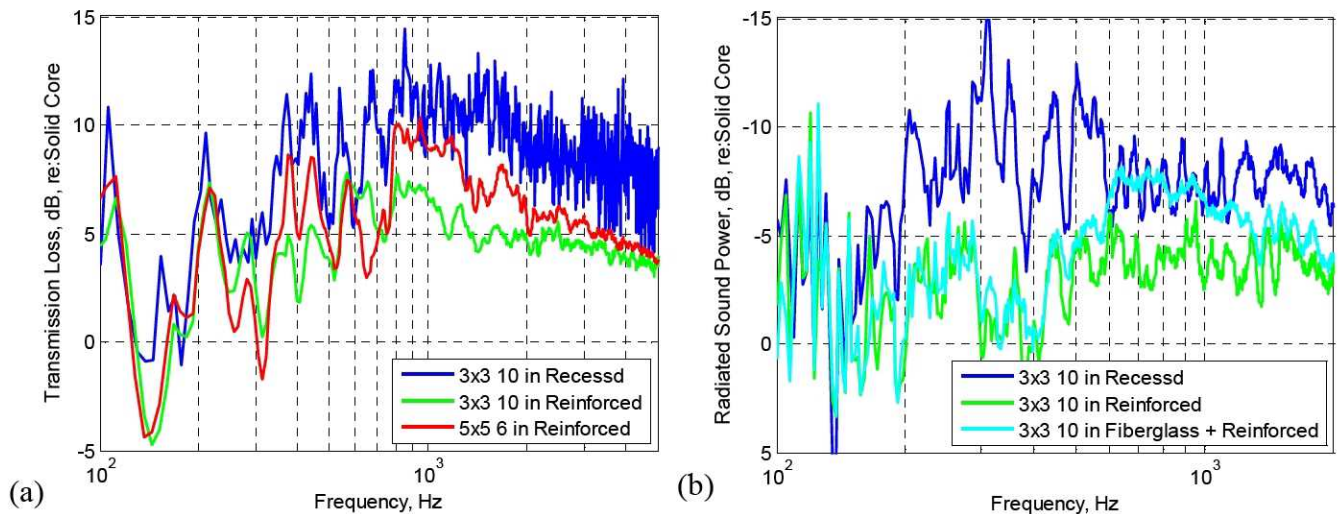
Average Difference in TL Over Frequency Band

Panel	100-500	500-1000	1000-2000	2000-5000
3x3 Rec	5.1	9.7	11.1	7.8
3x3 Rein	3.0	6.4	5.1	4.2
5x5 Rein	3.7	7.1	7.5	4.9

Average Difference in RSP Over Frequency Band

Panel	100-500	500-1000	1000-2000
3x3 Rec	7.5	7.8	7.5
3x3 Rein	2.0	4.0	3.7
3x3 Rein+Fiber	2.5	6.9	5.2

Fig. 14 Comparison of recessed core panels' performance, transmission loss (a), radiated sound power (b), band difference in TL, (c) and band difference in RSP, (d).

3.5 Deflection tests

An important requirement for the honeycomb panels is their ability to bear loads. As it became apparent that ample acoustic performance could be gained by milling sections of the core, attention turned to restoring the panel's load bearing ability. Finite element analyses indicated that reinforcing the core recesses with thin aluminum sheets could, depending on the configuration, restore the panel's strength. To test how well the reinforcing worked, deflection tests were performed on the solid core, recessed core and reinforced core panels. The deflection tests were done at 3 points as shown in Fig. 15 on the 'external' side of the panel (unmilled side) with the panel mounted in the SALT test window. Pressure was applied through a 5 lb (22.2 N) load cell and deflection measured with a dial indicator. The results of the tests are shown in Table 1 in μ in/lb. (0.056 micron/kg). The recessed panel deflection rate is an order of magnitude larger than the solid core panel. The recessed panel gained transmission loss, but it lost significant stiffness. The reinforced panel deflection rates are much closer to baseline with the maximum difference occurring at point 2 which deflected 40% more than the baseline. The optimized 5x5 panel's maximum difference also occurred at point 2, but was 100% greater than baseline. Recall that the 5x5 panel recesses were twice as deep as the 3x3 panel (1/2" vs. 1/4") reducing the thickness, and, therefore, the stiffness, of the reinforced section.
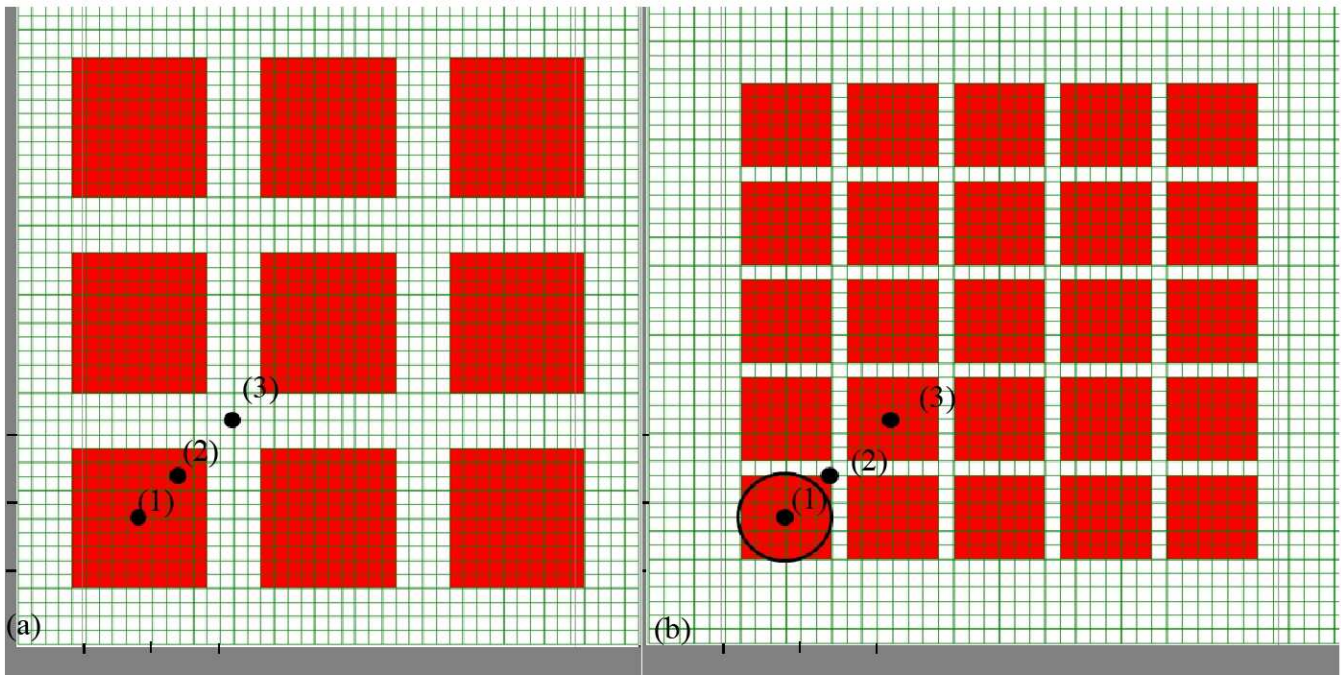

Fig. 15 Test points for deflection tests, 3x3 panels, (a) and 5x5 panels (b).

Table 1: Deflection Data

	Pt 1 μ in/lb.	Pt 2 μ in/lb.	Pt 3 μ in/lb.
Solid Core	300	390	500
Recessed, 3x3 10"	5000	3700	1200
Reinforced, 3x3 10"	360	540	660
Optimized, 5x5 6"	560	800	950

4. CONCLUSIONS

The reinforced/recessed panel design has shown promise. It has been demonstrated that substantial noise reduction can be obtained while panel strength and mass are maintained. The ultimate utility of this design approach depends on how well the panel features can be optimized for a particular application's requirements. The optimization performed thus far did not encompass the entire design space. For example, panel thickness was not varied from one design to the next and feature shape and orientation were uniform for each design. It is believed that the 'embedded double-wall' design will always return increased TL.

5. REFERENCES

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